EXPERIMENTAL TECHNIQUES IN BETA-SPECTROSCOPY*

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1. Introduction

The theory of all existing types of magnetic beta-ray spectrometers was discussed a few years ago in considerable detail and in a very able manner by Persico and Geoffrion.[1] From one point of view the present article might be considered as an extension of that paper. The facts presented there give the prospective builder of a beta-ray spectrometer an excellent insight into existing spectrometer models and provide a means whereby he can decide what and how to build to obtain certain desired characteristics, especially the desired resolution and luminosity. The theories associated with the operation of a magnetic beta-ray spectrometer have been presented in a thoroughly adequate manner in that paper. However, there are a number of existing facts and techniques which cannot be predicted so clearly in terms of a theoretical treatment but have generally been found in an experimental manner. They are all rather important to any person interested in building a beta-ray spectrometer for the first time and who desires to profit by the experiences of others rather than taking the longer path of learning by his own mistakes. It is the purpose of this paper to compile a listing of these experimental findings with appropriate discussion of each. For these purposes the consideration of the spectrometer is divided into four parts. They are the source, the detector, the intermediate regions within the spectrometer vacuum system and the spectrometer equipment exclusive of vacuum chamber.

1. E. Persico and C. Geoffrion, Rev. Sci. Inst. 21, 945 (1950)

II. Source

(a) Preparation of the Source

For the purpose of this discussion, the overall source will be considered as consisting of three parts, the source itself, its immediate backing, and the mounting which holds it in position.

There are two important factors to be considered in preparing a source, its uniformity and its thickness. Ideally, it is desireable to have a uniformly distributed source which is just as thin as possible but of sufficient strength to be recorded in the spectrometer. Of course, as in many other endeavors, an ideal source (having considerable strength but of zero thickness) is impossible, so one must compromise at some reasonable figure.

The most commonly used method for preparing a beta-ray spectrometer source, by chemical deposition of a solution of the source onto a backing with subsequent drying under a heat lamp, usually does not lead to uniformity of the source. Autoradiographs of such sources have shown[2] variations in intensity of the radiations

2. L. M. Langer, R. D Moffat and H. C. Price, Phys. Rev. 76, 1725 (1949)

from different parts of the source of as much as 100 to 1. An average thickness under these circumstances is rather meaningless since the thicker portions of the source cause distortions in the lower energy portion of the beta spectrum, as was observed[3] for such

3. C. S. Cook and L. M. Langer, Phys. Rev. 73, 601 (1948)

sources in the case of Cu^{64}. Of course, if the source material is carrier free and the amount of the solids in the solution is very small[4] the variation in local thicknesses will not reach sufficient

4. R. D. Albert and C. S Wu, Phys. Rev. 74, 847 (1948)

absolute magnitude to produce effective distortions in the results.

Some means are available, however, which guarantee the production of a uniform source. The first of these is a thermal evaporation technique. This method has been used[2,5] to prepare

5. G. E Owen and C. S Cook, Phys. Rev. 76, 1726 (1949). Method described by G. E. Owen, C. S. Cook and P H. Owen, Phys. Rev., 78, 686 (1950).

sources which show that the shapes of the Cu^{64} beta-spectra actually do conform to the predictions of the Fermi theory for allowed transitions. The chief difficulty encountered in this method of production

is that one finds it difficult to limit the deposition of the source to the spectrometer source holder. Activity may easily be distributed to other parts of the evaporating system. A modification of the method used for the production of the Cu^{64} sources does, to some extent, limit the spread of the activity. This is done by an initial chemical deposition of the source material on one side of a tungsten ribbon which will be used as the filament for the evaporation process. The source holder is next brought into the region facing the tungsten ribbon. The source may then be deposited by the evaporation technique without loss of more than a small quantity of source material. Thin, uniform sources of P^{32} have been deposited by this means. In certain cases it is also possible to separate different elements and get rid of certain superfluous solids by this technique.[6]

6. C. W. Sherwin, Rev. Sci. Inst. 22, 339 (1951)

Provided one uses a conducting backing it is also possible to electroplate certain sources and thereby insure uniformity of source. However, to electroplate requires that the backing foil be of sufficient thickness to be strong mechanically and conduct well electrically. Such backing can be used only for higher energy measurements because of backscattering from the backing of the very low energy radiations. It also limits the material to something to which a source can be electroplated. For a discussion of the limitations of such a backing see the following section on source backings.

A gaseous source is uniform.[7,8] However, the gas must be contained. This creates the necessity for materials to surround the gas thereby creating added scattering material. Also, a foil having sufficient strength to withstand the pressure between gaseous source and the vacuum within the chamber of the spectrometer must cover the source. This adds artificial thickness to the source.

7. M. Ter-Pogossian, F. T. Porter and C. S. Cook, Rev. Sci, Inst, 22, 389 (1951).

8. H. Brown and V. Perez-Mendez, Phys. Rev., 75, 1276 (1949); 78, 649 (1950).

Sometimes there seems to be no other good way to prepare a source except by deposition of a chemical solution onto some backing

material. Langer has found[9,10] that, under such circumstances, very

9. L. M. Langer, J. W. Motz and H. C. Price, Phys. Rev. 77, 798 (1950).
10. L. M. Langer, R. D. Moffat, and H. C. Price, Phys. Rev. 79, 808 (1950).

rapid drying of the deposited solution by means of an infra-red lamp coupled with a slight agitation of the liquid source prevents the formation of large crystals and produces a relatively uniform source.

Sometimes the source material can be prepared into the form of a fine powder. In such cases it is possible to prepare an acceptable source for many measurements by scattering this powder onto the gummed side of a piece of scotch tape after which any material which does not stick is shaken off the backing. However, to use this method one must be very careful to ascertain that the powder is extremely fine. The individual grains of powder having a slightly course texture may produce the same distortion in the spectrum as a thick source even though the measured average thickness indicates a thin source.[11] This is identical with the effect produced by the non-uniformaties in many chemically deposited sources.

11. C. S. Cook and L. M. Langer, Phys. Rev. 74, 548 (1948).

(b) Effects of Source Thickness

In case a beta-spectrometer source is of finite thickness those electrons whose paths begin near the back of the source must travel through the source before emerging into the spectrometer. During their flight through the source they will be degraded in energy by means of ionization and excitation of the atoms in the source. Because of scattering their actual paths may be longer than the measured thickness of the source material.

The effect of such degradation in energy is to distort the observed spectrum of the isotope being studied. A good example is the effect on the beta-spectra of Cu^{64}. Earlier non-uniform chemically-deposited sources of Cu^{64} showed[3] an excess of low energy beta-particles whereas later thin uniform evaporated sources of the same isotope showed[2,5] a great reduction in this excess.

This degradation in energy has also been observed[12] for internal conversion electrons as well as for beta-spectra.

12. G. E. Owen and H. Primakoff, Rev. Sci. Inst. 21, 447 (1950).

The effect is more noticeable at lower energies than at higher energies.

A very similar effect has also been observed in the case of photoelectrons produced by gamma-rays in an external converter.[13] The external radiator, usually a foil composed of some element of high atomic number, is the effective electron source. Thicker sources produce poor resolution, both for internal and external conversion. This is a result of the degradation of electron energy by the source material. The only thing about the peak which seems not to shift is the extrapolation to zero intensity of the high energy edge of the line. This then appears to be the portion of the line which must be used for calibration.

13. W. F. Hornyak, T. Lauritsen, and V. K. Rasmussen, Phys. Rev. 76, 731 (1949).

It appears that to obtain a true spectral shape a source whose thickness approaches zero is desired. However, some compromise must be reached between thickness and source strength.

One further effect of source thickness which may cause discrepancies in results is illustrated through the study of the high energy beta-spectrum of Sc^{46}. The isotope Sc^{46} has two gamma-rays (0.89 and 1.12 Mev). A study of the spectrum above the known end-point (0.36 Mev) of the main group of beta-rays reveals a continuous spectrum at least part of which is usually a distribution of Compton electrons produced in the source by the gamma-radiation[14]. Since the externally converted photoelectrons will in this case appear at the same energy as those internally converted a small portion of the intensity of the observed internal conversion lines may actually be the result of photoelectrons externally converted within the source.

14. F. T. Porter and C. S. Cook, Phys. Rev. 81, 640 (1951)

(c) Source Backing

Ideally one desired no backing for a beta-ray source. This has been approached only in the case of the proportional counter in which the source is introduced as a part of the counter's gas[15].

15. S. C. Curran, A. L. Cockroft and J. Angus, Phil. Mag. 40, 36, 53, 522, 1014 (1949); H. W. Wilson and S. C. Curran, Phil. Mag. 40, 631 (1949).

Even in this case a correction factor is sometimes necessary for events which occur near the wall of the counter. Unless one can use extremely high pressures[16] within the counter this technique is limited to the study of very low energy electron radiations

16. H. W. Fulbright and J. C. D. Milton, Phys. Rev., 76, 1271 (1949)

from a radioactive nucleus for sources which can be prepared in gaseous form.

In order to use a magnetic spectrometer the exact location of the source must be defined. This means that some sort of solid material must hold the source in place. Any material used for mounting the source will produce a certain amount of backscattering of the electrons and gamma-rays from the source There is experimental evidence[17] which shows that an increase in backing thickness

17. Englekemeir, Seiler, Steinberg, Winsberg and Novey, paper 5 Radiochemical Studies: The Fission Products; C. D. Coryell, N. Sugarman Editors, NNES, Vol. IV-9 (McGraw-Hill Book Co., Inc., 1951)

for very thin backings produces a much larger increase in the amount of electron backscatter than do further increases of the same amount after the backing has become quite thick. This, of course, is reasonable, since electrons have a finite range in material and any increase in the backing thickness beyond some critical point will produce no additive effect. This has been shown to take place for a thickness of material about 1/5 that of the range of the electron[17]. To obtain a correct spectral shape for low energy electrons therefore will require greater care in selection or preparation of backing than for higher energy electrons.

The amount of backscattering also depends upon the atomic number of the backing material. For a given energy electron, materials having higher atomic number produce a greater amount of backscattering than does one whose atomic number is lower[17,18]. It

18. D. Christian, W. W. Dunning, and D. S Martin, Jr., Nucleonics, 10, No. 5, 41 (1952); H. H Seliger, Phys. Rev. 88, 408 (1952)

is therefore desirable to have a backing with as low an atomic number as possible.

These two factors make certain foils, such as zapon[19], nylon[20], formvar[21] and LC600[22] ideally suited as backing material.

19. The preparation of zapon foils in this laboratory has followed techniques similar to those described by J. Backus (Phys. Rev. 68, 59 (1945)) for the preparation of collodian foils.

20. J. Richards, J. Brown, F. Felber and D. Saxon, Phys. Rev. 75 331 (1949). J. Brown, F. Felber, J. Richards and D. Saxon, Rev. Sci. Inst. 19, 818 (1948). These papers discuss the preparation of nylon foils for backings.

21. Preparation of thin formvar foils is described by V. K. Zworykin, G. A. Morton, E. G. Ramberg, J. Hillier and A. W. Vance, Electron Optics and the Electron Microscope (John Wiley and Sons, Inc. 1945) pp.244-245.

22. L. M. Langer, Rev. Sci. Inst. 20, 216 (1949) discusses the use of LC600 as source backing material.

The chief limitation on these backing materials is that they are non-conducting. If the source is not properly grounded, charging of the source (or of certain spots on the source) may occur, thereby distorting and shifting the observed spectrum[23,24]. A

23. C. H. Braden, G E Owen, J. Townsend, C. S. Cook and F. B. Shull, Phys. Rev. 74, 1539 (1948).

24. D. G Douglas, Phys. Rev 75, 1960 (1949).

number of methods for connecting the source dectrically to ground through an aluminum strip or a hair, made conducting by application of a collodial graphite dispersion, have been used The evaporation of a thin lsyer of copper on the reverse side of a zapon foil also has been used[25] to provide uniform grounding of the spectrometer

25. L. M. Langer and R. D Moffat, Phys. Rev. 88, 689 (1952)

source. Charging in negatron emitting sources may be prevented, or at least greatly reduced, by supplying a low density cloud of electrons in the immediate vicinity of (immediately behind) the source[26]. This has been shown to keep the negatron emitting source

26. J. L. Wolfson, Rev. Sci Inst. 22, 280 (1951).

very near ground potential.

One can overcome any dielectric effects through use of a metallic foil as the backing material. However, certain limitations enter into the use of such foils, chief among which is the desire

for a material having low Z. Beryllium is not easy to handle and can be rather dangerous if proper precautions are not taken. Carbon cannot be adequately formed into a thin foil. There is a strong chemical reaction between magnesium and a very large number of the solutions which are used to prepare sources. Besides its density and atomic number is not greatly different from aluminum, which, for most purposes, is the best of the metallic backings which can be used. An aluminum backing 0.00025 inch thick does not produce a distortion in the measured beta-spectrum of Cu^{64} in the region above 50 kev[5].

If, however, an electroplated source is desired, aluminum is not too satisfactory. Graphite (0.010 inch thick)[27] and Copper (0.0005 inch thick) have been used successfully as backings for

27. C S. Cook and L. M. Langer, Phys. Rev. 73, 1149 (1948).

electroplated sources.

Thin backings to which sources may be electroplated have also been prepared[28] by evaporating a thin layer of copper onto a

28. S. K. Haynes, private communication.

zapon backing. The plate then was deposited onto the copper. The zapon provides mechanical strength.

The chief limitation on the use of metallic conducting backings is that there is no certainty as to the lower energy limit for which one can obtain a true spectrum. This problem has not been thoroughly investigated. The 0.00025 inch aluminum has been shown to be safe to 50 kev.[5] Of course this lower energy limit of safety is not established for the organic foils either. However, experiments[9] on Pm^{147} tend to indicate a safety to 5 or 6 kev provided other limitations are also within this range.

In certain cases the use of solid or very thick backings is completely justified. Electrons scattered into the spectrometer from the backing must be scattered through very large angles. The probability for such scattering is very small. This means that most such scattered electrons have traveled through a considerable distance within the backing before returning to the spectrometer's electron beam. As a result of this distance traveled these electrons

will have lost considerable kinetic energy through ionization and excitation of the atoms within the backing material. Their kinetic energies then will be considerably lower than their initial energy. Also because of the random nature of their paths, their distribution of energies may be considerable. For measuring gamma-ray energies, internal conversion electrons have been studied[29,30] using very thick backings. The scattered

29. J. W. M. DuMond, L. Bogart, J. L. Kohl, D. E. Muller and J. R. Wilts, An Axial Focusing Magnetic Beta-Ray Spectrometer of High Lumnosity, Resolving Power and Precision, California Institute of Technology Special Tech. Report No.6, March 1952.

30. A. Hedgran and D. Lind, Arkiv f. Fysik 5, 1, 29, 177 (1952).

electrons not only are distributed over a relatively large range of energies, thereby producing only a slight increase in spectral intensity, but also appear at such degraded energies that they in no way affect the internal conversion line spectrum resulting from the direct radiation electrons.

In addition to backing material another related problem is the matter of material in the vicinity of the spectrometer source. Generally speaking the first baffle of the spectrometer should not lie in the immediate vicinity of the source. If such is the case the high radiation flux sometimes produces undue scattering into the normal beam path. Also, any possible electron paths from any portion of the source holder should be traced in order to avoid scattering of electrons from these parts into the spectrometer's measured electron beam. All parts of the source holder should be built at sufficient distance from the source to prevent such scattering. Special care must be taken in the larger magnetic spectrometers since these distances between source and holder must be appropriately larger to gain the advantages of a large spectrometer.

(d) Photoelectron Source

The measurement of gamma-ray energies and intensities are customarily made in beta-ray spectroscopy by making measurements on the secondary electrons to which these gamma-ray give their energy when they interact with matter. Such events take place both as internal conversion, in which case the electron is ejected by the radioactive atom in lieu of a gamma-ray, or by external conversion, in which case the gamma-ray from a radioactive atom interacts with an

electron belonging to another atom.

These interactions normally produce a continuous Compton distribution and a series of photoelectron peaks. Since energy values are more easily determined from a peak than from a continuous distribution it is customary to attempt to emphasize the photoelectron peaks in an external conversion measurement of gamma-ray energies. The cross section for the photelectric process increases[31] as Z^5.

31. W. Heitler, Quantum Theory of Radiation (Oxford University Press, 2nd Ed. 1944) p.123.

Use is therefore made of materials having high atomic number for these studies. Usually lead, thorium or uranium foils are used. Of course thinner foils produce better resolution[13] but thicker foils produce a larger number of electrons. The foil should always be sufficiently thin for all photoelectrons to escape with negligible loss of energy. For most experiments of this type foils having surface densities in the range from 5 mg/cm^2 to 50 mg/cm^2 have been used.

A typical photoelectron source is prepared by placing the source material inside a container of low or medium atomic number (quite often brass or copper) whose thickness is just sufficient to prevent the escape of beta-particles. The thin foil, to serve as the source of photoelectrons, is fastened securely to that surface of this container facing the spectrometer's vacuum chamber. The back of the source should also be covered to prevent distortion of the spectrum caused by the scattering of electrons from the walls of the spectrometer.[32]

32. E. N. Jensen, L. J. Laslett, and D. J. Zaffarano, Phys. Rev. 80, 862 (1950); 86, 1047 (1952).

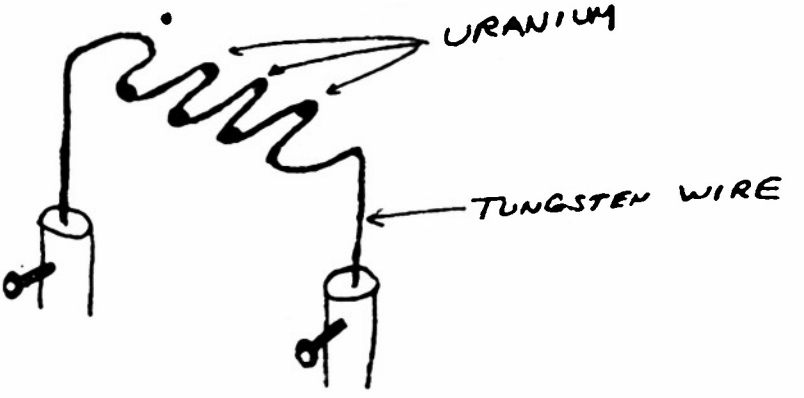
The thin foils,,known as radiators, which serve as sources for the photoelectrons, may be rolled to a reasonable degree of thinness from lead. However, very few laboratories are prepared to handle and roll thin foils of uranium. This can sometimes be done through special arrangements with one of the National Laboratories.

Thin foils of both lead and uranium have been thermally evaporated[10,33] in vacuum. Vacuum evaporation of lead is very

33. A. Hedgran and D. Lind, reference 27 and private communication.

simple since only low temperatures are required. However, the evaporated layer is extremely delicate and is easily rubbed off the surface onto which it has been evaporated. Vacuum evaporation of uranium is more difficult because of the higher temperatures required. The uranium must be very pure to have a reasonably low melting point. Furthermore if the uranium is in direct contact with the tungsten, an alloy of the two metals is formed with the result that the tungsten wire shortly crumbles. There seems, however, to be no tendency for the tungsten to evaporate with the uranium[33]. Hedgran and Lind[33] use a thick (~0.080 inch diameter) tungsten filament, shaped as illustrated in Fig. 1. The bends are filed

Fig 1.



flat and a small piece of uranium placed on each flattened region. The thick filament requires a large current such that the leads need artificially applied cooling. They use an old cyclotron ion source for the purpose. A diffusion pump having a speed greater than 100 leters per second is required to maintain the necessary vacuum. In this way they have prepared foils having thicknesses up to about 3 mg/cm^2. The thicker foils did not deposit uniformily; thus the method is suitable for the preparation only of very thin foils of uranium.

A number of methods for the preparation of uranium and other foils have been discussed by Dodson et al.[34] It is not known

34. Chapter 1 in Graves and Froman, Miscellaneous Physical and Chemical Techniques of the Los Alamos Project (McGraw-Hill Book Co., Inc., 1952).

by the author whether any of these techniques have been used for preparing thin uranium or thorium radiators for a beta-ray spectrometers. However, it seems that they may be worth investigation.

III. Vacuum System and Intermediate Regions of Spectrometer.

An important feature of a magnetic beta-ray spectrometer is a good evacuated region between the source and detector in which a magnetic analysis of the momenta of the electrons is made. The vacuum must be sufficiently good to prevent scattering of the individual electrons by gas within the chamber. An appropriate baffle system must be constructed which will surve the dual purpose of defining the path of the electron beam and preventing scattering into the spectrometer's detector of electrons which reach the walls of the vacuum system.

Within the vacuum chamber is one baffle which defines the beam. This for most magnetic spectrometers is located relatively close to the midpoint between source and detector. For photographic spectrometers it is, however, located closer to the source. The position and use of these defining baffles has been discussed in considerable length for different types of spectrometers by Persico and Geoffrion[1] in their discussion of beta-ray spectrometer design. It will therefore not be discussed in detail here.

The number of baffles within a spectrometer, exclusive of the defining baffle, has varied considerably among spectrometer designers. The prevalent ideas seem to lie between two extremes, one being that a large number of baffles are needed to define the beam and thus prevent scattering from the walls of the chamber, the other saying that a single defining baffle should be adequate. Otherwise, it is argued, considerable scattering will take place at the edges of the baffles.

An attempt was made[35] to study experimentally the basic

35. G. E. Owen and C. S. Cook, Rev. Sci. Inst. 20, 768 (1949)

features of these arguments and to arrive at some solution which will be adequate. As would probably be expected, the best arrangement seems to be an intermediate point of view. A single baffle is

inadequate; three baffles appear to be sufficient. Obviously, one desires to keep the number of baffles to a minimum to prevent excessive scattering from their edges facing the electron beam. Although the experiments were performed on a semi-circular uniform field spectrometer, the arguments regarding scattering from baffles can be applied equally well to other types of spectrometers.

An interesting feature of the experiment is the result which indicates that there is no significant change in the measured results caused by a change in the atomic number of the material from which the chamber or baffles are made. However, since it is known that less scattering takes place from materials having low atomic number, it is still felt that making chamber and baffles from materials of low Z is advisable.

Of importance, however, is the fact that the surface of the chamber and of the baffles must be electrically at ground potential. Otherwise a buildup of charge at some point in the spectrometer will distort the results obtained. If the system is made of some plastic material it is recommended that a good coating of colloidal graphite be applied to all surfaces with the added precaution that these surfaces be grounded.

The vacuum techniques which a beta-ray spectroscopist should know have been discussed in considerable detail by several authors[36]. Generally the path traversed by a beta-particle in a spectrometer does not exceed one or two meters, even in the larger spectrometers. If reasonable care is observed in following accepted

36. F. N. D Kurie, Rev. Sci. Inst. 19, 485 (1948); A. Guthrie and R. K. Wakerling, Vacuum Equipment and Techniques (McGraw-Hill Book Co., Inc., 1949); A. C. Graves and D. K. Froman, Miscellaneous Physical and Chemical Techniques of the Los Alamos Project (McGraw-Hill Book Co., Inc., 1952) see especially Chapter 5.

practices[30], no problems due to vacuum difficulties should arise. Commercially available diffusion pumps can easily produce a vacuum in which an electron's mean free path is considerably greater than one or two meters.

Most gaskets for the spectrometer vacuum system now are commercially available O-rings, as described by Kurie. These are

made from a low vapor pressure material and are available in a large variety of sizes. If, however, there are certain parts of the system where it is desirable to have extremely low vapor pressure from the gasket a foil of some soft metal may be used. Many people use[37] indium or lead gaskets (usually about 0.010 inch thickness)

37. M. Ter-Pogossian, J. E. Robinson and J. Townsend, Rev. Sci. Inst. 20, 289 (1949)

in any part of the system that will come in contact with the counter gas. This insures the non-existence of impurities from gasket material as a part of the counter gas.

IV. Detector

Two types of detectors are generally used in magnetic beta-ray spectrometers. The first, and most common, is the Geiger-Muller counter. The second is the scintillation counter with photo-multiplier tube detector.

(a) The Geiger-Muller counter

With regard to experimental techniques, there are four rather general groupings for the problems associated with G-M counters used in conjunction with magnetic spectrometers. These are (1) its construction, (2) its gaseous filling, (3) its window, through which pass those particles to be detected and (4) the electronic circuits needed for its operation. The efficiency of the counter for detecting beta-particles may depend on any of these items.

The theory of the operation of a G-M detector has been discussed by several authors[38]. No general comments will be made

38. H. G. Stever, Phys. Rev. 61, 38 (1942); B. Rossi and H. Staub, Ionization Chambers and Counters (McGraw-Hill Book Co., Inc., 1949); S. C. Curran and S. C Craggs, Counting Tubes-Theory and Application (Academic Press, Inc., 1949); D. H. Wilkinson, Ionization Chambers and Counters (Cambridge University Press, 1950).

here regarding the theory and operation of G-M counters. The references just cited do this adequately. The discussion will be primarily concerned with the use of G-M counters as detectors in magnetic spectrometers. Most of the counters so used must be constructed in the laboratory in order to provide the needed thin windows.

About the only precautions regarding the construction of G-M tubes is a warning to be careful. To make a G-M tube operate requires no special techniques. However, to make it operate in a uniform manner for long periods of time (which is necessary for effective operation of a beta-ray spectrometer) requires primarily cleanliness. Extreme care must be taken that all solder joints are left clean. Any flux which is used must be washed away. Otherwise, in certain cases, interaction between the counter gas and the remaining flux causes the gas to deteriorate. The central wire (usually between 0.003 and 0.010 inch diameter) must be free of points and pits. This can be ascertained under a microscope. Although tungsten is most commonly used for this purpose, small diameter wires of stainless steel work very well[39] and are much smoother. While not

39. L. M. Langer, private communication

so critical as the central wire the inside surface of the tube should be machined smooth. However, irregular features such as a side window can be introduced here without affecting the operation of the counter.

The gas used in the G-M counter consists of an inert gas (usually argon) plus a quenching gas. The choice of the quenching gas and its relative proportion differs greatly between laboratories. Ethylene is used in this laboratory[40]. Some commercially manufactured counters use other non-organic quenching gases which

40. See K. H. Morganstern, C. L. Cowan and A. L. Hughes, Phys. Rev. 74, 499 (1948).

supposedly give the counter infinite life from the point of view of number of counts recorded. However, with the thin windows used in beta-spectrometer counters refilling generally becomes necessary prior to the expected life of the organic quenching gas. Therefore organic quenching gas has been found thoroughly satisfactory.

Because they are expected to be used in a region of atmospheric pressure, many commercial counters are filled to nearly atmospheric pressure. However, since the spectrometer counter gas will be separated from the evacuated chamber of the spectrometer only by a thin foil of some type it is desirable to have as small a pressure

as possible within the counter. In the extreme, if too low a pressure is used, the efficiency of the counter for detecting electrons becomes distinctly less than 100 percent. This is caused by the fact that at lower pressures an electron may pass through the counter, especially through the shorter paths at the outer edges, without producing an ion pair, and therefore escape detection. For energies below 150 kev it is possible to use[9] a counter pressure as low as 2.0 cm. For higher energies the only tests with which the author is acquainted indicate a lower limit of about 4.9 cm pressure in order to assure 100 percent efficiency. Of course, there is the possibility that the efficiency may be a function of the type of filling mixture used as well as of the energy of the incident electrons.

Mica or aluminum counter windows are seldom if ever made which transmit electrons having energies less than about 35 kev. For this reason, when studies of low energy spectra are desired, foils made from the same types of materials used for source backings[19-22] are generally employed. The final window is prepared by putting together several layers of these thin foils. This is to avoid pin-holes through which the counter gas may leak. Even with this precaution the extremely thin foils required to study spectra below 5 kev tend to show a slow leakage of counter gas into the spectrometer vacuum system. The system most generally employed to overcome this gradual loss is one which keeps the counter at constant pressure by means of an automatic control. One such device is a mercury valve[37] and another is a cartesian manostat.[41]

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41. Rev. Sci. Inst. 21, 266 (1951). See also L. M. Langer and R. D. Moffat, Phys. Rev. 80, 651 (1950).

The biggest problem with G-M counter windows, however, is the matter of loss of energy and scattering as the electrons pass through these windows. In case the window is thicker than the range of the electrons, the electron energy is below the lower cut-off energy of the window and effectively no electrons pass through the window. If, at the other extreme, the electron energy is very much larger than the cut-off energy essentially all the electrons will pass right through the window into the sensitive region of the counter. It is the intermediate region which is the nemesis for the beta-ray spectroscopist. The rise in transmission between the cut-off energy and the energy at which there is 100 percent transmission is

a continuous gradual process in which the upper end has a shape which may be approximated by an exponential function approaching 100 percent assymptotically. The problem is very closely related to that of electron scattering in matter[17,18,42,44]. However, most of the theories of electron scattering[45-50] have been developed

42. G. Groetzinger, W. Humphrey and F. L. Ribe, Phys. Rev. 85, 78 (1952)
43. H. J. Lipkin, Phys. Rev. 85, 517 (1952)
44. W. Paul and H. Reich, Zeits f. Physik, 131, 326 (1952).
45. S. Goudsmit and Saunderson, Phys. Rev. 57, 24 (1940).
46. E. J. Williams, Rev. Mod. Phys. 17, 217 (1945).
47. G. Moliere, Zeits f. Naturforshhung 2a, 133 (1947); 3a, 78 (1948).
48. W. A. McKinley and H. Feshbach, Phys. Rev. 74, 1759 (1948).
49. H. S. Snyder and W. T. Scott, Phys. Rev. 76, 220 (1949); 78, 223 (1950)
50. S. Olbert, Phys. Rev. 87, 319 (1952).

primarily for high energy electrons. The energies at which the problem of partial transmission in G-M counter windows arises is in a much lower energy range.

To compare with the theory of electron scattering, measurements of the relative positron and negatron transmission through aluminum and platinum counter windows have been made.[51] Considering the several simplifying assumptions which were made in order to put

51. C. H. Chang, C. S. Cook and H. Primakoff, Phys. Rev., in press.

the theory into a form suitable for comparison, there is remarkable agreement between experiment and theory. It must also be indicated that to use such metallic foil windows, the window thickness was of necessity greater than that used in normal beta-ray spectroscopy.

The actual thickness of thin foils can be measured in terms of the wave length of a monochromatic beam of light by means of a Michelson interferometer.[52] Some technique such as this becomes

52. A. I. McPherson and D. G. Douglas, Rev. Sci. Inst. 20, 457 (1949).

necessary if transmission coefficients are to be accurately determined as a function of film thickness for very thin foils.

The only compilation of data known to exist at the present time for relative transmission coefficients for thin windows is one made by Saxon[53]. Saxon, however, expressed his data as a correction

53. D. Saxon, Phys. Rev. 81, 639 (1951). A set of transmission curves for thin nylon and formvar films has been determined by R. B. Heller, E. E. Sturcken and A. H. Weber, Rev. Sci. Inst. 21, 898 (1950). There is still some question in the author's mind as to which curve actually applies for the window of a G—M counter tube.

factor (the reciprocal of the transmission coefficient).

It must be remembered that the desired condition always is to measure 100 percent of the particles impringing upon the surface of a counter window. This is the reason for attempting to produce the thinnest possible window. The only time when a valid reason exists for using partial transmission coefficients is in case sufficiently thin windows are not available. A valid test to determine whether a window transmits 100 percent of the electrons impinging upon its surface can be made by measuring the transmission of two windows of differing thickness. If the number of transmitted electrons is the same in both cases it can be reasonably assumed that 100 percent of the electrons are getting through both windows.

Since windows of finite size are needed on the spectrometer counters, extremely thin foils sometimes do not have the mechanical strength to withstand the pressure between the gas in the counter and the vacuum of the spectrometer. Grid supports have customarily been used[9,29,54,55] in such cases. However, caution

54. L.M. Langer and C. S. Cook, Rev. Sci. Inst. 19, 257 (1948).
55. L. Feldman and C. S. Wu, Phys. Rev., 87, 1091 (1952).

must be taken to insure that the grid is sufficiently thick to prevent the transmission through it of any electrons and also to insure that grid edges are shaped properly to prevent partial transmission through them.

An attempt has also been made to build a "windowless" spectrometer.[9] The need for a continuous supply of gas to the counter presented its problems in this case. Also the trapping of all condensible vapors entering the spectrometer vacuum system limited the length of time during which a single set of data could be taken. Finally the detector in this case wasn't really windowless, since a finite amount of gas remained in the region between the sensitive section of the counter and the vacuum chamer.

The window problem has also been attacked through the use of accelerating potentials in an attempt to give low energy electrons sufficient additional energy for them to penetrate thin foils of finite thickness. If possible such an acceleration would be most feasible in the region between the final exit slit and the counter.[54] However, the application of voltage in this region has always been accompanied by an increase in the background counting rate.[54,56,57]

56. H. M. Agnew and H. L. Anderson, Rev. Sci. Inst. 20, 869 (1949)
57. D. K. Butt, Proc. Phys. Soc. London, 63A, 986 (1950)

The method has not been very successful because of this very large increase in background counting rate when voltages sufficiently large are applied to produce 100 percent transmission of all real electrons. The real counting rate is then usually only a small fraction of the background and does not lead to statistically accurate results.

It is also possible to apply the voltage at the source. However, unless extreme care is taken this may lead to spectral distortions. If the direction of acceleration is not the same as the original direction of travel of the emitted electron, this electron may be deflected either into or out of a path which eventually leads to the spectrometer's detector. A method utilizing acceleration at the source of a lens spectrometer has been used[58]. This makes

58. C. H. Chang and C. S. Cook, Nucleonics, 10, No. 4, 24 (1952)

use of the symmetrical characteristics of the region around the source such that a hemispherical source surrounded by a hemispherical grid keeps the electron emission symmetric in the forward direction.

At least two potential causes of the increase in background counting rate have been isolated. One source of electrons is thermionic emission. Townsend[59] has shown that an increase in the temperature of a copper sphere placed at the source position of the

59. J. Townsend, this department, private communication.

lens spectrometer increases the number of these very low energy electrons in a manner at least qualitatively in agreement with

expectations from the theory of thermionic emission. A cleaned tungsten filament, whose work function is considerably higher than the surface of copper sphere, shows no appreciable number of electrons until heated to a low red heat.

A very large number of very low energy electrons are also observed[60] to be emitted when a radioactive source has been placed

60. C. H. Chang, this laboratory, private communication

on a metallic sphere at the source position of the spectrometer. The number of these electrons is directly proportional to the strength of the source and has been observed to decay at the same rate as the source. These observations lead to the conclusion that secondary electrons are ejected from the surface of the spherical source as the beta-particles pass through the surface. Since the energy of such secondary electrons is most probably[61,62] only a few electron-volts, these should also appear to have an energy equal to the

61. K. G McKay, Advances in Electronics (Academic Press), 1, 66 (1948)
62. N. Schaetti, Zeits f. Angewandte Math. und Physik, 2, 123 (1951)

applied voltage.

Additional spurious counts are also observed[59] in the spectrometer when voltage is applied to the source in case the ionization gauge (for the measurement of the vacuum) is in operation. Possibly some of the ions produced in the gauge escape and get into the spectrometer's vaccuum chamber, are attracted toward the source and produce secondary electrons.

Based upon the above mentioned information, the cause of the increased counting rate, when voltage is applied between exit slit and counter, is not necessarily immediately evident. However, the solid angle subtended by the counter from the source is very small compared to the same solid angle from the exit-slit. A few cosmic rays producing secondary electrons can produce an appreciable effect in addition to thermionic electrons escaping from the appropriate surfaces. Also effects may result from the x-rays produced when accelerated electrons are stopped in one of the surfaces.

(b) Scintillation Counters

Scintillation counters are also now becoming important as detectors in magnetic spectrometers. The use of an anthracene or stilbene crystal and an RCA 5819, and EMI 5311[62a], or a DuMont photomultiplier tube produce such a detector. However, the photo-

62a. A. Sommer and W. E. Turk, Jour. Sci. Inst. 27, 113 (1950)

multiplier tube is very sensitive to changes in magnetic fields in its immediate vicinity. It is therefore necessary that the tube be removed some distance from the field of the spectrometer and that it be shielded in the best possible manner from stray magnetic fields.[63] Use of a scintillation detector with a lens spectrometer

63. Magnetic shields which will fit over an RCA type 5819 photomultiplier tube are manufactured by the James Millen Manufacturing Co., Inc., 158 Exchange Street, Malden, Massachusetts.

has been successfully accomplished by a number of groups[64,65,66].

64. Zeldes, Brosi and Kettelle, Phys. Rev. 81, 642 (1951)
65. R. M. Pearce and K. C. Mann, in publication
66. E. Jensen, Bull. Am. Phys. Soc., St. Louis meeting paper, W4 (1952).

Since the pulse height produced by the photomultiplier tube is proportional to the energy of the electron incident upon the anthracene crystal, a further energy selection can be made through use of a pulse-height discriminator in the detector electronic circuit. This has been done by Zeldes, Brosi and Kettelle[64] as a further selection technique for low intensity, high energy electrons in the presence of high intensity, low energy radiations in the spectrometer. Such selection greatly reduces the background counting rate of the detector, a problem in the case just mentiond because of the large number of electromagnetic quanta which may penetrate the lead shielding between source and detector and thereby increase the background counting rate, but which will produce secondary electrons of sufficiently low energy that they will be eliminated from the results by the pulse-height selection.

Pearce and Mann[65] have used an anti-coincidence technique using scintillation counters to increase their ability to observe low intensity photo-electrons in the presence of a large number of Compton electrons. In their technique the source is placed just under

the front face of a lucite light pipe and located so as to be at the spectrometer's source position. On the front face of the lucite is cemented a small flake of anthracene onto which is cemented a uranium or lead radiator. At the rear of the lucite pipe is a photomultiplier tube. The lucite acts as the absorber for the primary beta-particles. Compton electrons, generated in the lucite and in most of the crystal, and which are focussed toward the detector of the spectrometer, leave an identifying pulse which is recorded by the source photomultiplier just mentioned. Photoelectrons, on the other hand, leave no such pulse. An anticoincidence circuit between source photomultiplier and the spectrometer's detecting crystal system prevents the final recording of any pulse seen by both detectors. However, those pulses seen only by the detecting crystal system will be recorded. This will include only photoelectrons from the radiator and Compton electrons produced in the radiator itself. This method has been used[65] to detect new low intensity transitions in Ta^{182} and Sb^{124}.

Jensen[66] has used a lens spectrometer equiped with scintillation counter and a scintillation spectrometer to measure coincidences between gamma-rays and their appropriate beta-groups. This is a very useful technique in the study of nuclear disintegration schemes. Actually K Siegbahn has done even better[67] and built two lens spectrometers back to back for this same purpose. Fowler and

67. K Siegbahn, Arkiv f. Fysik 4, 223 (1952)

Schuffler have also built a coincidence spectrometer[68] in which a

68. C. M. Fowler and R. G. Schuffler, Rev. Sci. Inst. 21, 740 (1950).

single vaccuum chamber but two detectors are used. In this case there is no problem regarding the effective shielding of one magnetic field from another. However, there is a problem regarding adequate baffling in order to properly select the electron energies to be measured.

One precaution should be made in the use of lucite light paths. The plastic used should be cast rather than extruded. Strains and other irregularities in the extruded material sometimes act to deter the effective passage of light quanta between the crystal at

one end and the photomultiplier at the other. Effective passage of the quanta along the lucite rod also depends upon good reflection at its walls. If angles of incidence cannot be made large enough in all cases to provide total reflection, a good reflecting material, such as powdered magnesium oxide, should be packed around the exterior of the rod.

The use of scintillation counter detectors has not as yet provided a means for eliminating the window transmission difficulties of a G-M counter, since the efficiency of the scintillator plus photomultiplier apparently does not remain near 100 percent for low energies[66,69].

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69. W. H. Jorden, "Detection of Nuclear Particles", Annual Review of Nuclear Science 1, 207 (1952).

(c) Electron Multipliers

As a matter of record it must also be added that an electron multiplier can be used as a detector of electrons[69a].

69a. J. S Allen, Rev. Sci. Inst. 18, 739 (1947).

In this case the electron beam enters directly into the multiplier, strikes the first electrode and starts the avalanche which is ultimately observed by means of some electronic equipment. Since there is no window the electron multiplier should be ideal for the detection of low energy particles, in which case the window reduces the efficiency of a G-M counter, or insufficient production of quanta within the crystal reduce the efficiency of a scintillation counter. However the efficiency of a photomultiplier tube is far from linear for electrons (see Fig. 10 of Allen's article[69a]). It also depends greatly upon the prior treatment of its electrodes. Since it is often necessary to let air into a beta-ray spectrometer, some method for adequate treatment of the electrodes under vaccuum within the spectrometer is necessary.

The electron multiplier is, however, very good for the detection of heavy particles and has been used for the detection of recoil protons[69b,69c,69d].

69b. J M. Robson, Phys. Rev 78, 311 (1950); Phys. Rev. 83, 349 (1951); A. H. Snell, F. Pleasonton and R. V. McCord, Phys. Rev. 78, 310 (1950).

69c. C. W. Sherwin, Phys. Rev. 82, 52 (1951).

69d A. H. Snell and L. C. Miller AECD-1956(A48)

V. The Magnetic Field

Accurate determination of electron spectra in magnetic beta-ray spectrometers depends critically upon the proper functioning of the spectrometer's magnetic field.

In the first place, it is important to design and construct the spectrometer such that the correct field exists in all regions of the electron path. Secondly, it is necessary to measure the strength of this field with an accuracy at least equal to the accuracy to which a knowledge of the electron momenta is desired. Finally, one must be able to control the field such that during any single measurement the field will remain constant to a degree equal or better than the accuracy to which the momenta are desired.

The first is principally a design and construction problem. If the spectrometer utilizes iron to locate its magnetic field, proper selection of the type of iron and of the cross sectional dimensions are important. Uniform density, especially in the regions near the pole face, must be maintained so that no measureable distortions will exist in the desired field shape. In order to keep the magnetic flux inside the iron yoke, the cross sectional area of the magnetic circuit should at all points be sufficiently large, and the iron should be of sufficiently low carbon content, so as not to approach the saturation conditions of the iron, even for the highest fields which will be used.

The pole face gap should be sufficiently large to prevent the electron beam from approaching too close to the face of the pole. Even pole faces which have been made of material of uniform density and have been precision ground to present an optically flat surface, show considerable fluctuation, and even an occasional discontinuity, in the immediate vicinity of the iron surface (say within 1/10 inch of the surface).[70] Such fluctuations rapidly wash

70. C. R. Bruce and G. E. Pake, private communication. Field strength measurements were made by a nuclear resonance.

out, however, with increasing distance from the iron. In the case of the 40 cm radius of curvature magnet spectrometer built by Langer and Cook[54], it is found that, although many sharp edges exist in the pole face, a region one inch high centered in the median plane between the pole faces shows the same field shape at any horizontal level. The pole fact gap is four inches.

In the case of a spectrometer, such as a lens or solenoid type which uses little or no ferrous material in its construction, the problem of establishing and shaping a magnetic field reverts to the proper positioning of a set of current carrying coils. The simplest such devices are the thin lens which uses a single series of coils half-way between the source and the detector, and the uniform solenoid which utilizes a single long coil in which the source and detector are placed at such positions that there is no gradient of field parallel to the walls of the cylindrically shaped coils in the region between source and detector. Many multiple coil arrangements have been made in order to achieve a desired field[71]

71. See references 1 and 26 for further discussion of these instruments.

One important problem in this type of device is the elimination of that component of the earth's magnetic field perpendicular to the coil produced field. This is usually done by means of large Helmholz coils.

An arrangement consisting of three coils also has been developed[72] for the purpose of neutralizing the earth's magnetic

72. S. K. Haynes and J. W. Wedding, Rev. Sci. Inst. 22, 97 (1951).

field in and around a lens type magnetic spectrometer.

Elimination of a vertical component of the field has also been effected by directing the axis of the spectrometer parallel to the earth's magnetic field.[72a]

72a. E. A. Quade and D. Halliday, Rev. Sci. Inst. 19, 234 (1948); E. N. Jensen, L. J. Laslett and W. W. Pratt, Phys. Rev. 75, 458 (1949).

Once a magnetic field is established, it then becomes the problem of the spectrometer operator to devise a suitable method for measuring that field. The measurement must be made to an accuracy sufficient to measure the momentum ($B\rho$) of the electron to the desired number of significant figures. The measurement must also be made in a short enough period of time that it will represent a true measure of the magnetic field at the time of study of a single portion of the electron spectrum.

One of the oldest and most commonly used techniques is the "flip coil and ballistic galvanometer" technique. A coil consisting

of a large number of turns of very fine wire is mounted in the magnetic field such that the plane of the coil is perpendicular to the direction of the magnetic field. The coil is rotated quickly through an angle of 180°. The change in magnetic flux through the coil thus produced develops a voltage across the flip coil which in turn causes a certain quantity of charge to flow through the circuit consisting of the flip coil and the ballistic galvanometer coil. The flux change will, in this case, be proportional to the magnetic field, and, if the period of the ballistic galvanometer is long compared to the time required to flip the coil, ~~the galvanometer is long compared to the time required to flip the coil~~, the galvanometer deflection will be proportional to the amount of charge which flows in the circuit, and therefore proportional to the spectrometer's magnetic field.

There are three significant features which may produce difficulties in this type of magnetic field measurement. One is the time required for the ballistic galvanometer to return to zero before another measurement can be made. If this is made too short, the second difficulty arises. This is the matter of making certain that the time required to operate the flip coil is short compared to the period of the galvanometer. If the galvanometer's period is too short, there is a spread in readings depending upon the time required to operate the flip coil. Some compromise must be reached between these two items and is usually arranged by adjusting a series and shunt resistors for the galvanometer to a condition of critical damping. A third error lies in the ability of the operator to read the galvanometer. The scale used for reading the deflection can usually be read to no better than about 0.2 of a millimeter. This shows the need for a large scale deflection. However, if conditions are prepared for a large scale deflection the ability to read the scale is diminished by the fact that the galvanometer spends a proportionally shorter period of time at this larger deflection. Here, again a compromise must be reached.

The element of time required for a magnetic field measurement has been greatly reduced through use of a continuously rotating coil within the magnetic field. Such a device has been constructed[73]

73. W. M. Cork, R. G. Shreffler and F. B. Shull, Rev. Sci. Inst., 18, 315 (1947).

and its speed kept constant by means of a synchronous motor. Its output current is a measure of the magnetic field strength. Later, two modifications of this method have been used as magnetic field measuring devices. Both eleminate a problem which arises from the fact that contact resistance may change between a set of brushes and the rotor with which they make contact and from which they take the potential to be measured. The modified versions also eliminate the possibility of error which might be caused by a change of frequency on the incoming electric lines, thereby changing the speed of the synchronous motor, and the resultant field measurement. These two items become quite important if it is desireable to read the magnetic field strength to four or five significant figures. The first of these methods[74] eliminates the difficulty with brushes by

74. L. M. Langer and F. R. Scott, Rev. Sci. Inst., 21, 522 (1950).

using a pair of transformers, the primary coil of which rotates on the same shaft as the continuously rotating coil within the field, and the secondary of which is fixed and may be directly connected to a measuring device. This of course produces an alternating current. This current is, however, relatively easy to measure by mixing it with another A.C. signal from a similar rotating coil in a known field produced by a pair of Helmholtz coils. The two coils are rotated by a pair of identical synchronous motors operated 180° out of phase from a single source of power. Any change in external frequency will thereby change the speed of the two motors at the same rate and produce no overall change in output signal. By adjusting the field produced by the Helmholtz coils the two signals can be made equal and the exact field determined by a null method. Measurements to better than one part in 1000 can be made by this method.

The other system which has been constructed[75] utilizing

75. A. Hedgran, K. Siegbahn and N. Svartholm, Proc. Phys. Soc. 63A, 960 (1950). See especially pp. 971-974.

this method is very similar to the system constructed by Langer and Scott. However both rotating coils are placed on the same shaft

and are oriented so as to provide voltages 180° out of phase with each other. This eliminates the need for two synchronous motors, almost any motor will now be satisfactory. This system can make magnetic field measurements to five significant figures.

A third method, in this case primarily applicable to the measurement of uniform magnetic fields within a beta-ray spectrometer, utilizes nuclear resonance absorption[76]. For accuracy of

76. G. E Pake, Am. Jour of Physics, 18, 438 and 473 (1950).

measurement this appears, when applicable, to be the best of the techniques. For a single sample showing nuclear magnetic resonance, the frequency which must be applied to the sample to produce resonance conditions is a linear function of the magnetic field. The radio frequencies used can be measured to many significant figures and, as a result, present no error in this type of measurement. Momentum ($B\rho$) measurements can be made using these techniques after the spectrometer is calibrated in terms of applied frequency (ν). Through the technique introduced by Lindström,[77] calibration can be

77. G. Lindström, Arkiv f. Fysik, 4, 1 (1952), see especailly section IV of this paper.

made if two different internal conversion lines from the same nuclear transition can be measured in the spectrometer. Lindström uses the K and L_I conversion electrons from ThB. Since x-ray transitions are generally known to at least five significant figures the energy of seperation (ΔW) between two such lines can generally be expressed to five significant figures. In terms of the electron momenta $p_1 (= AH_1\rho)$ and $p_2 (= AH_2\rho)$, respectively, for the two conversion electrons, A being a constant of proportionality

$$W = (p_1^2 + 1)^{1/2} - (p_2^2 + 1)^{1/2}$$

$$= \left[(AH_1\rho)^2 + 1\right]^{1/2} - \left[(AH_2\rho)^2 + 1\right]^{1/2}$$

Dividing by $H_2\rho$

$$\frac{W}{H_2\rho} = \left[\left(\frac{H_1}{H_2}\right)^2 A^2 + \frac{1}{(H_2\rho)^2}\right]^{1/2} - \left[A + \frac{1}{(H_2\rho)^2}\right]^{1/2}$$

All quantities are known or can be determined experimentally with an accuracy of at least five significant figures, with the single exception of the quantity $H_2\rho$. Since any other field H_n will produce a resonance at a frequency ν_n, any electron momentum may be measured by means of the ratio $H_n\rho/H_2\rho = H_n/H_2 = \nu_n/\nu_2$.

This method of measuring magnetic fields has also been used by DuMond et al.[28]

Adequate control of the spectrometer's magnetic field is also of considerable importance, especially if high resolution is desired. During the taking of a single set of data it may be necessary to keep the field constant to one part in several thousand. Generally speaking, if the control current remains constant the magnetic field will also remain constant. To produce the necessary magnetic field in an iron core type spectrometer only a small current is usually necessary. A very successful type of electronic control for the magnetic field is a modification of a constant current circuit designed by Elmore and Sands.[78] It must of course be realized that any change in the current will produce a change in the

78. Elmore and Sands, Electronics, NNES, Vol. V-1 (McGraw-Hill Book Co., Inc., 1949) pp.390-393.

magnetic field, but that a return to the original current will not bring about a return to the original field because of the hysteresis in the iron. Elmore and Sands' circuit when working properly will keep the current sufficiently constant for good spectrometer measurements. Instead of the resistance steps indicated in Fig. 7.14 of Elmore and Sands it has been found that the use of three high voltage rheostats[79] provides the necessary continuity for setting the spectrometer to any magnetic field. Grid bias for the 807 and 6AG7 has been provided by "B" batteries of small dimension[80]. For long life

79. Such as Ohmite model "K" vitreous enameled rheostats.

80. Such as Eveready's Models 467 ($67\frac{1}{2}$ volts) and 455 (45 volts) or Olin's Model 1710 ($67\frac{1}{2}$ volt) and 6211 (45 volt).

the batteries which supply the current for the plate circuit of the 1B4P must be larger "B" batteries[81]. The battery which supplies the

81. Such as Eveready Model 487 (45 volts)

filament current for the 1B4P should be a rechargeable wet cell[82].

82. We have found Willard plastic non-spill types ER 24-2 or ER 34-2 most convenient for this purpose. A circuit can be designed such that these cells can be rechared from a regular battery charger when the spectrometer is not in use without removing the battery from its position in the rack.

The grid bias on the 1B4P must remain constant with extreme accuracy if the system is to work properly. Mallory mercury "A" batteries maintain their voltage within extreme limits at 1.345 volts during almost their entire life[83]. They are also

83. L. N. Langer, private communication.

unaffected by temperature, humidity and shock. Their small size allows them to be built in a pile to supply the needed 1B4P grid voltage without consuming very much space. The most common source of instability in the circuit has been found to be caused by loose elements in the 6AG7 or 807 tubes. Tubes which test as good in a normal tube tester may not work in this circuit. A good check for loose elements may be made by placing the tube in place in the circuit, set the magnet current at some readable figure and then top the tube with a pencil. If any grid elements are loose a fluctuation in magnet current will occur.

To produce the required fields in lens and other spectrometers not utilizing an iron yoke, larger currents have generally been used. Provided conditions in the immediate vicinity of the spectrometer are kept relatively constant, the magnetic field is directly proportional to the current which flows through the spectrometer's coils (plus a small additive constant necessitated by the earth's magnetic field -- this usually being appreciable only for low energy radiations).

The current for these spectrometers has generally been provided by motor-generator sets, whose field coil currents are regulated by some sort of feed-back from the magnet current. Although designed for nuclear magnetic resonance measurements, a typical current stabilizer has been described by Sommers et al.[84]

84. H. S. Sommers, P. R. Weiss and W. Halpern, Rev. Sci. Inst. 22, 612 (1951).

This device measures the D.C. current from a standard resistance, and feeds it back through an A.C. converter to an amplifier, whose output controls the field current in the motor-generator set. Good current regulation is the result.

Magnetic field regulation can also be made through use of a proton resonance to control the output from the motor-generator set. This has been utilized by DuMond in his new beta-ray spectrometer.[85]

85. See reference 29, pp.24-27. See also M. E. Packard, Rev. Sci. Inst. 19, 435 (1948).

The feedback system is essentially the same as that described by Sommers et al.[84] However, the error signal comes from the signal produced by the proton resonance inside the magnetic field. The control therefore cannot have an error because of non-linear relationships between coil current and magnetic field. This type of control can thus be used for all types of spectrometers, regardless of the amount of iron in their structure. About the only limitation is that the resonance head must be located in a region of uniform field strength in order to provide a sharp proton resonance.